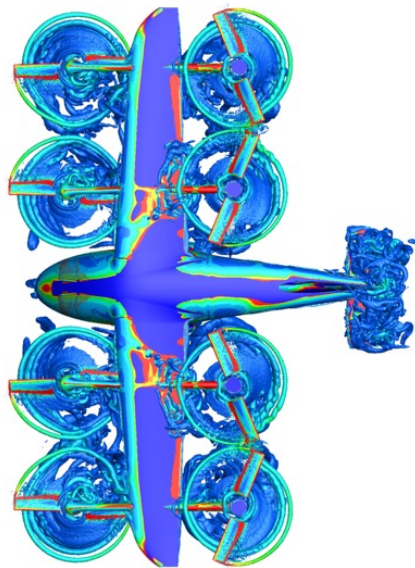


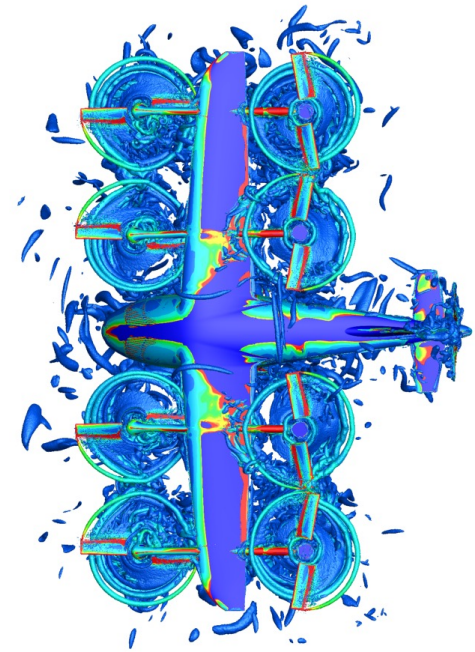


High-fidelity Simulations of Lift+Cruise VTOL Urban Air Mobility Concept Aircraft in Hover



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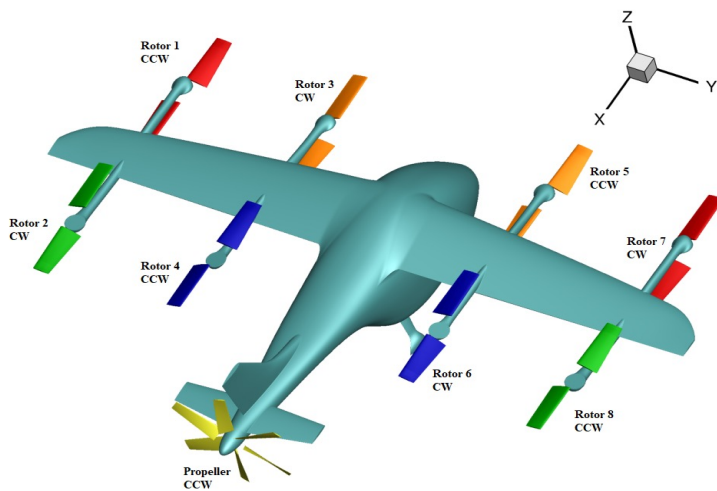
AIAA SciTech Forum 2024
January 09, 2024





Motivation

- AIAA Rotorcraft Hover Prediction Workshop calls for general calculations for eVTOL or UAV aircraft in hover.
- NASA Revolutionary Vertical Lift Technology (RVLT) Project supports research in studying urban air mobility (UAM) aircraft and operations.
- The lift+cruise VTOL aircraft is one of the several conceptual configurations recently presented in NASA UAM research¹



The lift+cruise concept is a thrust-and-lift compound VTOL aircraft.

- Cruise flight (airplane mode)
- **Hover flight (helicopter mode)**
- Low-speed forward flight (transition mode)
- RVLT Project also supports development of cutting-edge technology and tools for analyzing and designing VTOL vehicles that can operate safely and reliably with reduced environment impact.
- The objective of this work is to demonstrate capabilities of a high-fidelity multidisciplinary analysis tool to capture the strong unsteady flowfield around this multirotor aircraft in hover.

1.Silva, C., Johnson, W., Antcliff, K.R. and Patterson, M.D. "VTOL Urban Air Mobility Concept Vehicles for Technology Development." AIAA 2018-3847, 2018. ²



Multidisciplinary Analysis

CFD solver

- FUN3D² is a node-centered unstructured-grid flow solver developed at NASA LaRC.
- Widely used for high-fidelity analysis and adjoint-based design of complex turbulent flows.
- The negative variant of Spalart-Allmaras turbulence model with rotation correction (SA-neg-R) is used.
- Yoga³, a new overset-grid assembler for large-scale unstructured-grid systems, is available within FUN3D V14.

Comprehensive analysis (CA) model

- The Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics II (CAMRADII)⁴ code is used for structural dynamics analysis of the rotor blades and aircraft trim.
- Collective pitch trim
- **Rotor rotation-speed trim**

2. <https://fun3d.larc.nasa.gov>

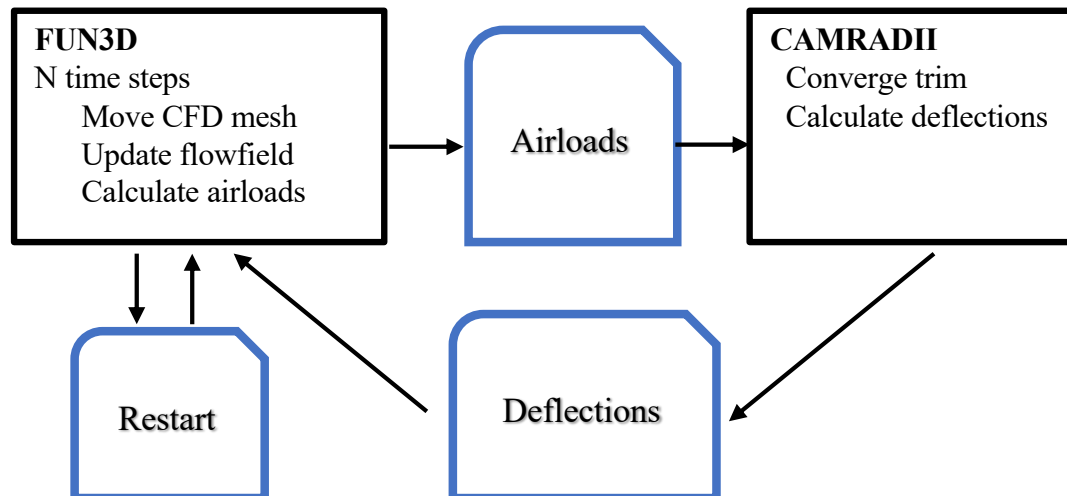
3. Druyor, C., "Enhancing Scalability for FUN3D Rotorcraft Simulations with Yoga: an Overset Grid Assembler," AIAA 2021-2746, 2021.

4. Johnson, W., "Rotorcraft Aerodynamic Models for a Comprehensive Analysis," AHS 54th Annual Forum, 1998.



Loose Coupling Process

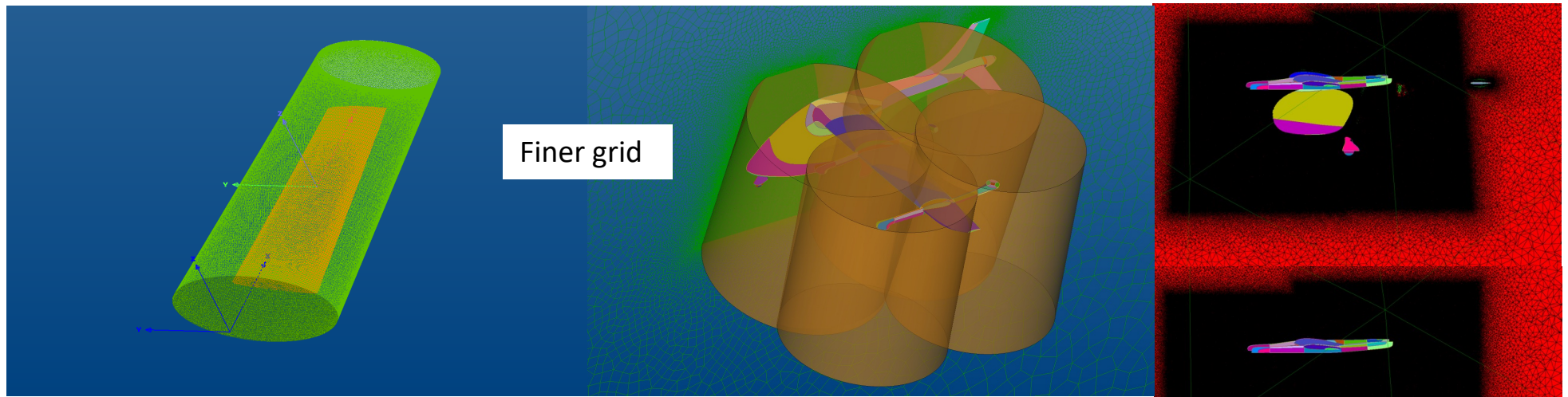
- File-based loose-coupling workflow
- Interactions between CFD and CA at the end of each coupling cycle
- Alternate executions of FUN3D/CAMRADII with bash scripting



CFD Composite Grid Systems

Composite, overset, unstructured-grid systems are assembled with Yoga

- Four types of component grids generated with Pointwise.
- Two grids were used for hover simulations.
- “Baseline” grid has 208 million grid points and “Finer” grid contains 394 million grid points.



- Blade near-body grid (4.2M points)
- Max edge length <7.5% mean chord
- Shortest distance to wall $1E-05$ ($y^+ \approx 1$)

- Fuselage background grid (320M points)
- Enlarged clustering source regions
- Source spacing parameter < 5% mean chord
- Source region around propeller removed

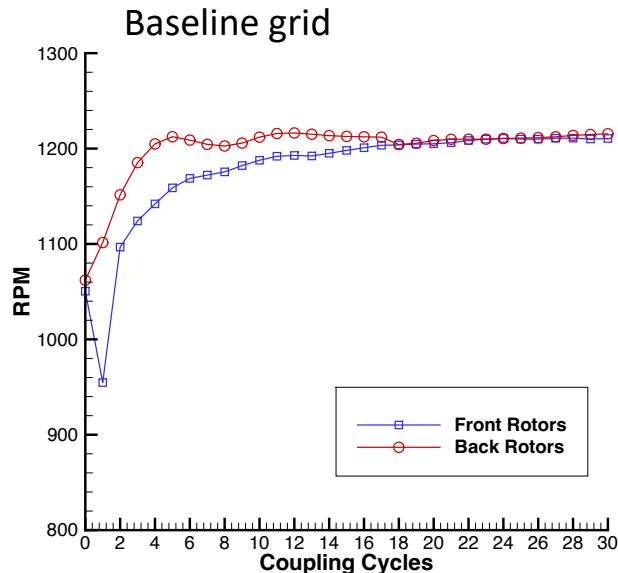


Hover Conditions and Coupling Cycles

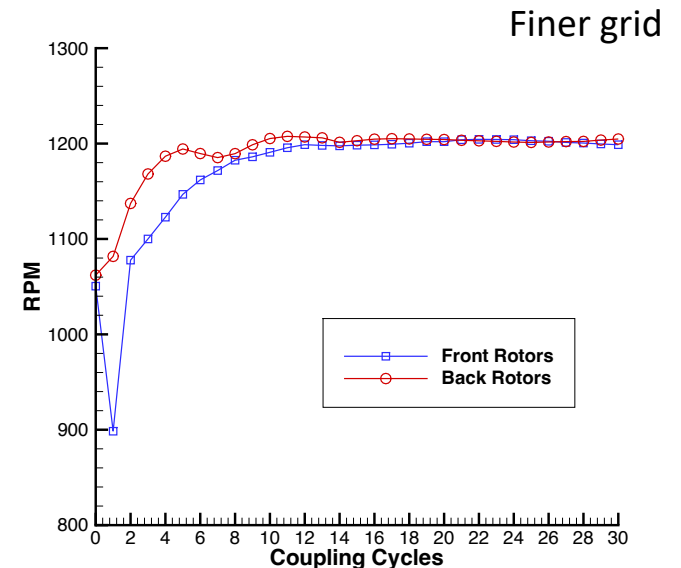
- Lifting rotors initial rotational speed is 1050.42 rpm (revolution per minute).
- CAMRADII uses rotor rotation-speed control with trim targets of net z-force, x-force and y-moment to be zero (aircraft weight 5903 lb).
- In current CAMRADII trim setting, four front rotors are linked together to maintain the same rotation speed and the four back rotors operate at the same rotation speed.
- CAMRADII specifies three trim parameters: front-rotor rotation speed, back-rotor rotation speed, and the aircraft pitch angle.
- In CAMRADII trim, the airframe (fuselage, wings, tails etc.) aerodynamic forces and moments are set as zero for hover simulations.
- FUN3D uses a time-step of 0.5 degree of azimuth advancement (720 time steps per revolution) based on the slowest rotor, exchanging data with CAMRADII at every half rotor revolution, except the 1st cycle which takes one revolution in CFD.
- A total 31 coupling cycles (16 revolutions) were performed for both baseline and finer grids.



Rotor Rotation Speed Trim Results



- In the transient cycles, the back-rotor speed is higher than the front-rotor speed.
- The final rotation speeds of all rotors are almost the same.
- The difference between two grids is small ($< 1\%$).



Hover: Trim variables over the final coupling cycle.

Trim Variables	Baseline Grid	Finer Grid
Airframe Pitch Angle (degrees)	-0.05	-0.07
Front-rotor Speed (rpm)	1210.54	1198.79
Back-rotor Speed (rpm)	1215.51	1204.79



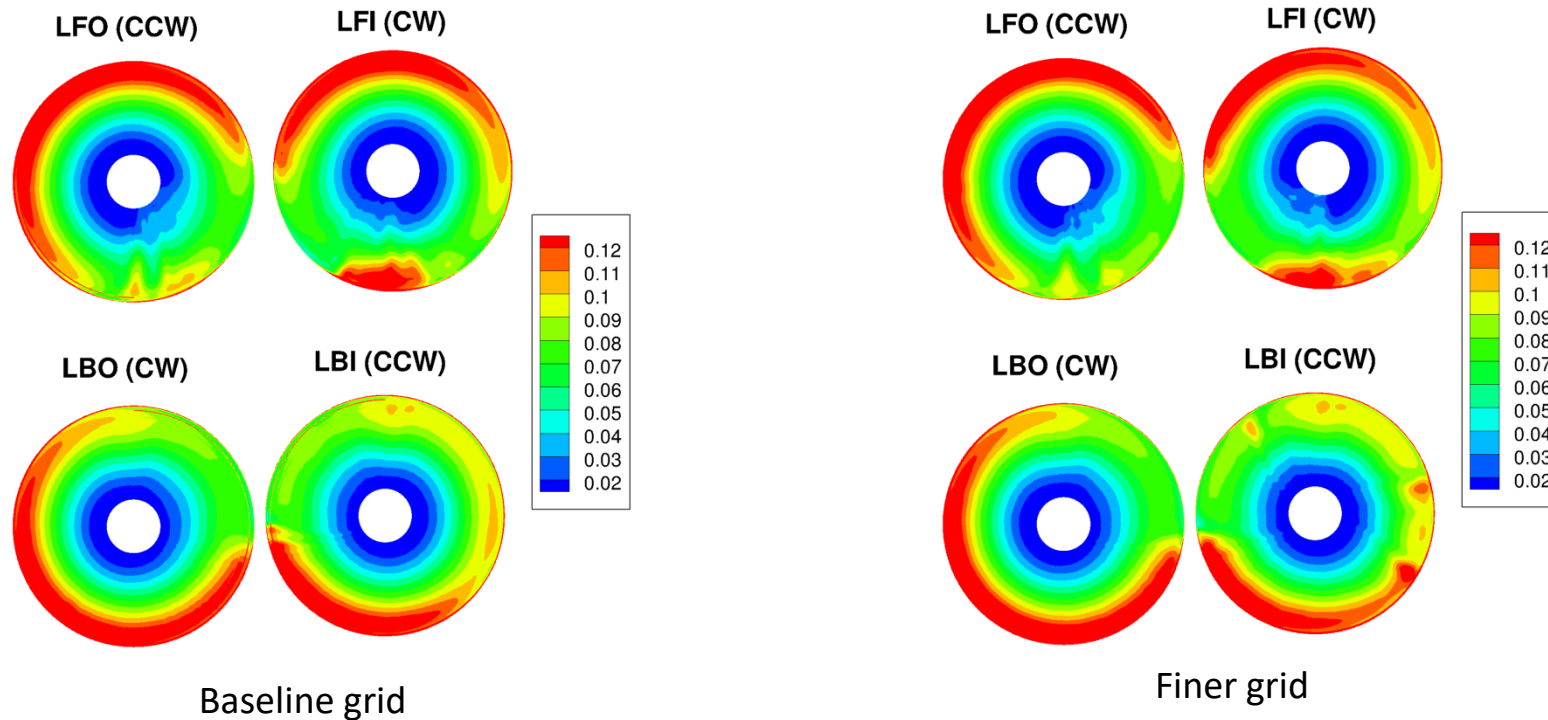
Rotor Performance

- Figure of merit (FM) is defined as $FM = \frac{C_T^{3/2}}{2\sqrt{C_p}}$.
- Overall rotor thrust and torque are higher using the baseline grid.
- On the finer grid, FM is higher for the outboard rotors due to better tip vortex resolutions; FM is lower for the inboard rotors, where the strong rotor/fuselage wake interactions are better captured (maximum difference < 1.4%).

Rotor	Baseline Grid			Finer Grid		
	Thrust (lb)	Torque (lb-ft)	FM	Thrust(lb)	Torque(lb-ft)	FM
LFO	752.80	463.39	0.6418	750.99	461.68	0.6481
LBO	770.93	476.69	0.6439	759.98	470.68	0.6440
LFI	733.25	469.27	0.6093	719.19	463.36	0.6052
LBI	738.95	468.68	0.6146	723.89	461.82	0.6101
RFI	734.80	468.95	0.6016	714.11	463.37	0.5988
RBI	740.78	469.19	0.6162	726.42	463.74	0.6108
RFO	751.65	464.56	0.6387	749.64	460.76	0.6476
RBO	768.62	475.85	0.6421	762.49	471.56	0.6459
Total	5991.78	3756.58		5906.71	3716.97	

L – Left, R – Right, F – Front, B – Back, O – Outboard, I – Inboard

Normal Force on Rotor Disk Planes

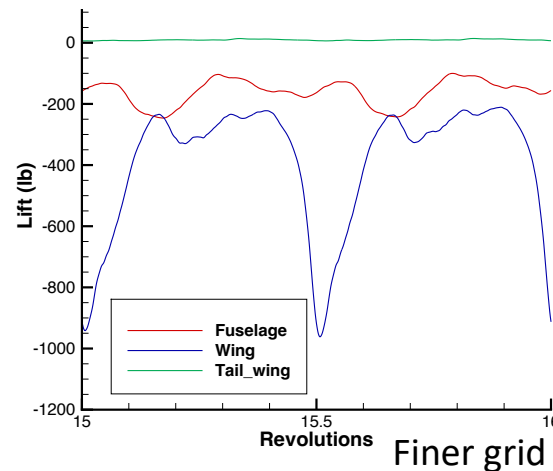
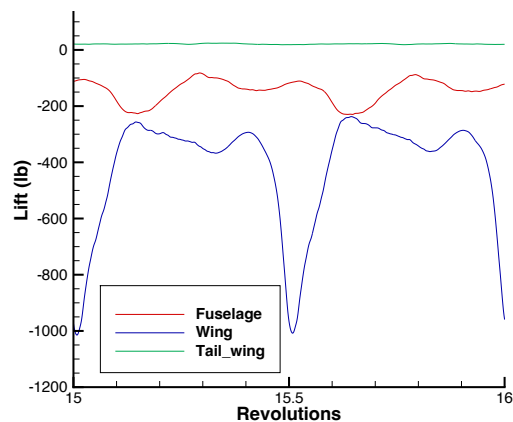
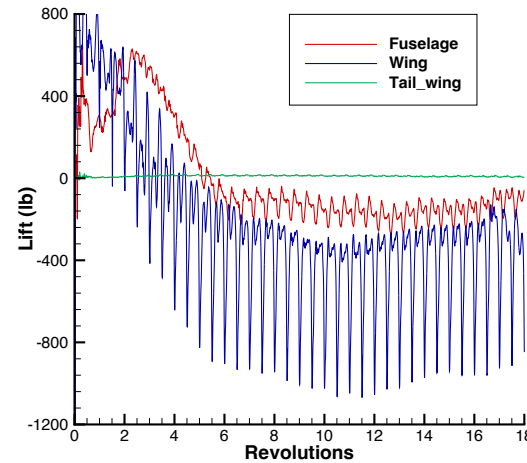
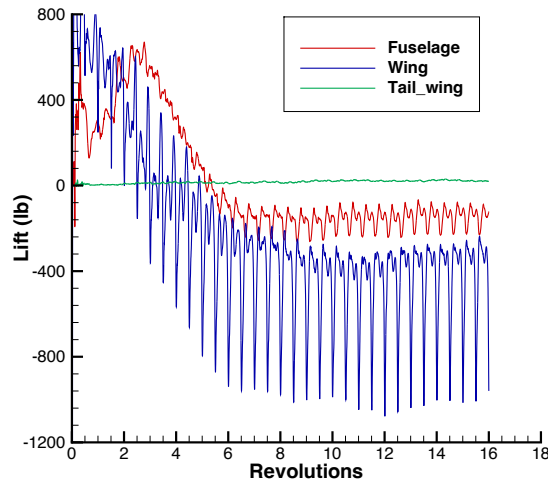


**Sectional normal force (M^2C_N) of the lifting rotors in hover
(Rotors on the left side are compared)**

L – Left, F – Front, B – Back, O – Outboard, I – Inboard



Airframe Lift



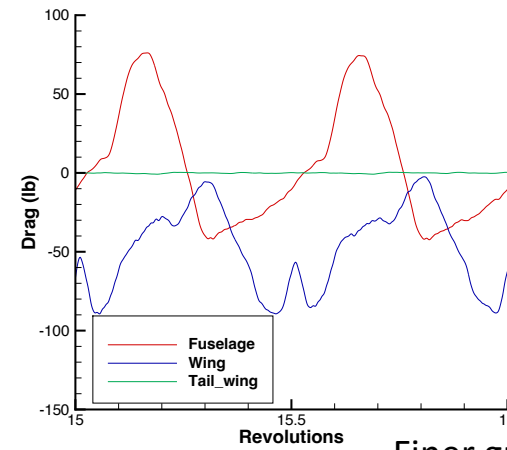
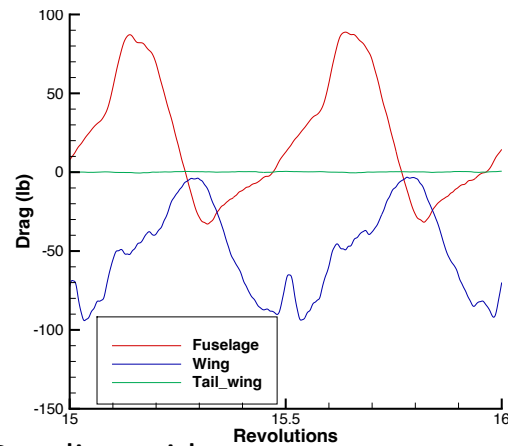
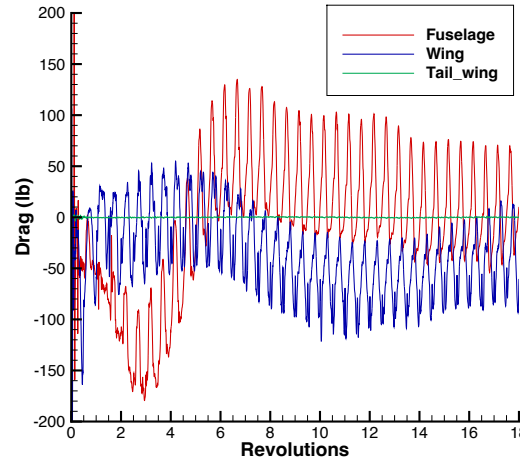
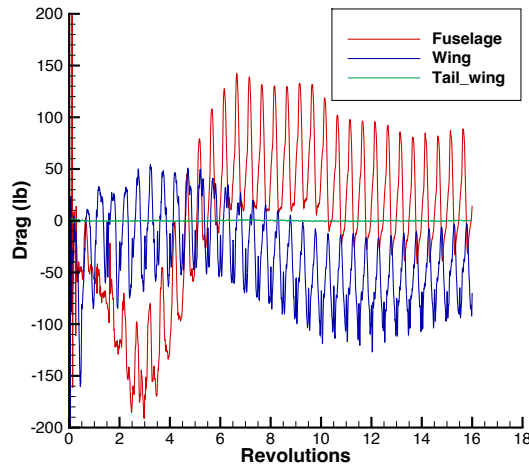
Baseline grid

Finer grid

- The lift+cruise aircraft airframe is divided into three groups: 1) fuselage with landing gear and vertical tail, 2) main wings, and 3) horizontal tail wings.
- Strong downwash flow is observed.
- The dominant frequency is $2/\text{rev}$.
- Large variation of lift on the wings indicates strong rotor wake interactions
- Lift variation on the fuselage is not as large as that on the wings, and the lift on the tail wings is relatively small.
- Compared to the baseline grid, the lift variations on the fuselage and wings computed on the finer grid are similar, while showing more unsteady flow patterns.



Airframe Drag



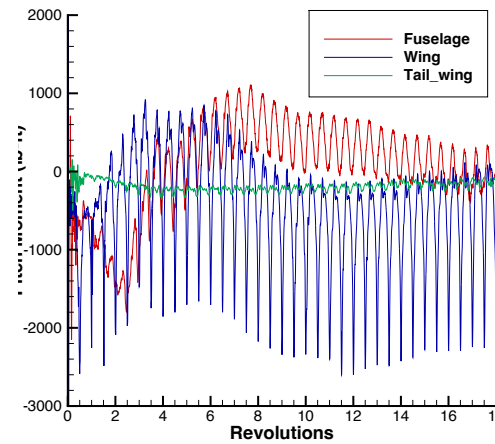
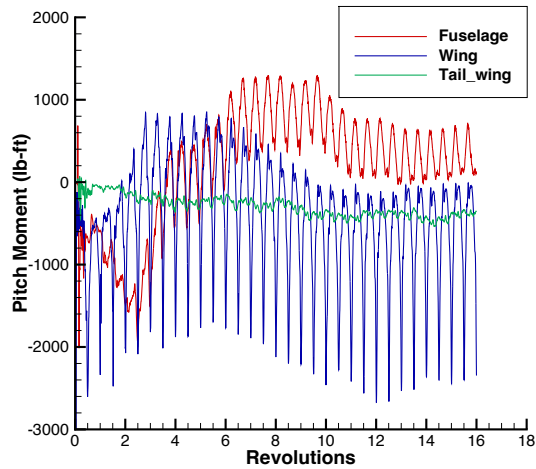
Baseline grid

Finer grid

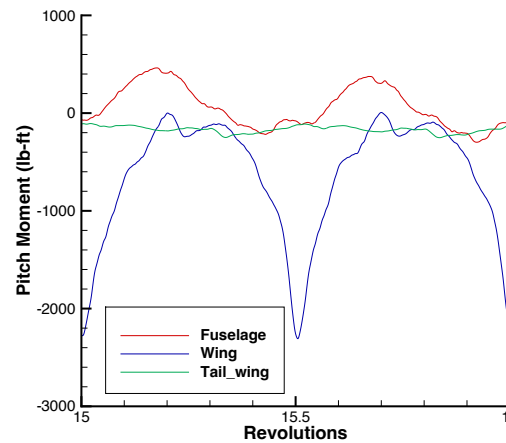
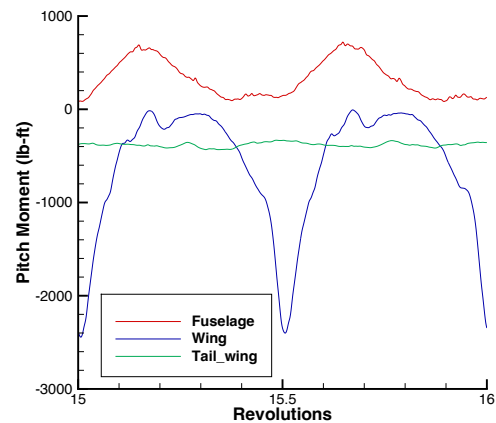
- Drag is designated as the horizontal force along the positive x-axis direction.
- The frequency of the drag variation remains consistent at 2/rev.
- The amplitude of the drag oscillation is significantly smaller compared to lift.
- Some drag cancellation from fuselage and main wings is shown .
- The drag on the tail wings is nearly zero on both baseline and finer grids.



Airframe Pitching Moment



- Pitching moment on the wings shows very large variation while the pitching moment on the fuselage is comparatively small.
- The negative pitching moments produced by the vertical force on the tail wings are not negligible on both grids.
- The refined grid region around the propeller blades applied on the baseline grid has been removed in the finer grid systems.
- The differences in lift and pitching moment on the tail wings between the two grids indicate additional grid refinement studies around the horizontal tails may be desired.



Baseline grid

Finer grid

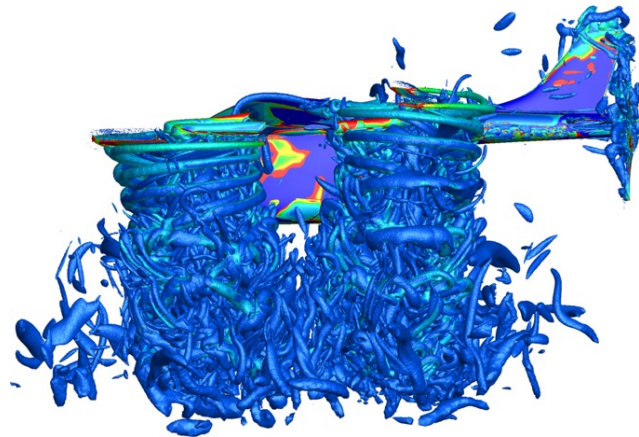
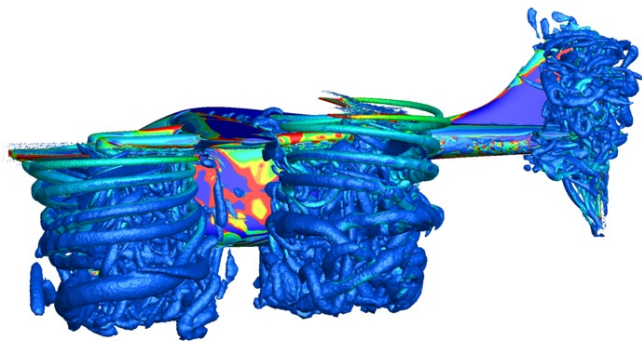
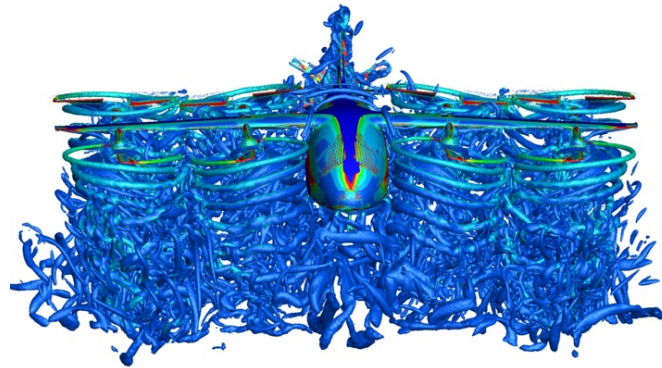
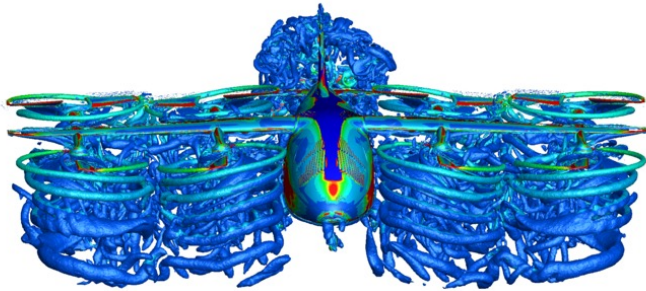


Mean Airframe Forces and Moments

Airframe component	Baseline Grid			Finer Grid		
	Lift (lb)	Drag (lb)	Pitching moment (lb-ft)	Lift (lb)	Drag (lb)	Pitching moment (lb-ft)
Fuselage	-144.77	20.79	324.38	-161.70	4.18	62.58
Wings	-417.49	-51.24	-608.69	-388.97	-48.47	-638.18
Tail-wings	21.17	0.13	-382.05	9.35	-0.08	-168.33
Total	-541.09	-30.32	-666.36	-541.32	-44.37	-743.93

- The total averaged values of lift, drag and pitching moment on the airframe are reasonably close to each other between the baseline and finer grid results.
- The total negative lift from the airframe is close to 10% of the vehicle weight and the negative pitching moment is also not negligible.
- Currently CAMRADII assumes the airframe forces and moments are zero in the trim cycles for hover.
- The FUN3D/CAMRADII coupling workflow will be further tested to include the mean airframe forces and moments computed by FUN3D in the CAMRADII trim process.

Flowfield Visualization



Baseline grid

Finer grid

- Isosurfaces of Q-criterion colored by the vorticity magnitude.
- In the baseline-grid case, the lifting rotor tip vortices and details of secondary vortices and wake interaction are successfully captured.
- The inboard rotor wake interactions beneath the fuselage are only captured with the finer grid.
- Less vortex structures near the propeller on the finer grid with removal of the refined grid region in background near propeller.



Concluding Remarks

- High-fidelity, multidisciplinary simulations have been performed for the NASA lift+cruise VTOL UAM concept aircraft in hover using rotor rotation-speed trim to demonstrate the capabilities of the coupled framework for simulations of complex multirotor aircraft with strong rotor wake interactions.
- The multidisciplinary analysis tool is based on the loose coupling workflow of the FUN3D CFD solver and the CAMRADII comprehensive analysis model.
- Two grid systems are used. Simulations on these grids provide comparable solutions, where the finer grid resolves more wake interactions among lifting rotors and between rotors and the airframe.
- The simulation results from the rotor disk planes and the airframe components reveal a strong unsteady flowfield surrounding the lift+cruise aircraft during hover.



Future Work

- Improve the coupling workflow by providing the averaged airframe forces and moments in FUN3D to the CAMRADII for trimming considerations at each coupling cycle.
- Employ the hybrid RANS(SA-neg-R)/large-eddy simulation (LES) model to further study the turbulence model effects on rotor vortices and wake interactions.
- Further verification and validation can also be performed with comparisons with experimental or other computational data when they become available.



Acknowledgements

The NASA Revolutionary Vertical Lift Technology (RVLT) project funded the work reported here.

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Thank You !

